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Evaluation of bulk method for satellite-derived latent heat flux

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[1] To establish the most accurate bulk method for estimating the satellite-derived latent heat flux (LHF), we evaluate four bulk methods by using direct eddy correlation and inertial dissipation fluxes obtained during 15 cruises in the tropics and midlatitudes. According to our results, the coupled ocean-atmosphere response experiment (COARE) version 3 is the best algorithm for estimating the satellite-derived LHF. Moreover, to clarify the error sources when measuring the satellite-derived LHF including errors in meteorological values, we evaluated the LHF errors as an error function of the meteorological values. If we assume that the reported RMS error for the satellite-derived meteorological values is valid, the RMS error of the LHF derived from instantaneous satellite data is estimated to be approximately 35–55 W/m^2. The error determined by the bulk method contributes to 30–50% of the RMS error of the LHF.

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1. Introduction

[2] Ocean surface latent heat flux (LHF) transfers heat from the ocean to the atmosphere by a phase change of water. LHF and sensible heat flux (SHF) are also called turbulent heat flux (THF), because they depend on the ocean surface turbulence. The ocean surface flux has four components (i.e., shortwave radiation, longwave radiation, LHF, and SHF), and LHF is the second largest component in the ocean surface heat budget [*Chou et al.*, 2003]. Moreover, the variability of the net surface heat flux with timescales exceeding a day is dominated by LHF [*Tomita and Kubota*, 2004]. Therefore, LHF is essential for understanding the ocean surface heat budget. In addition, LHF plays a crucial role in the global hydrological cycle, because LHF is directly related to the ocean surface evaporation. Thus, LHF is crucial for understanding not only the ocean surface heat budget but also the global freshwater budget.

[3] LHF is directly calculated from the covariance of humidity with vertical velocity such that

$$LHF = \rho_a L_v \overline{w'q'}, \tag{1}$$

where ρ_a is the density of air, L_v is the latent heat of vaporization, w' and q' are turbulent perturbations of the vertical velocity and humidity, respectively, and is the mean of the covariance between w' and q'. There are several ways to estimate the LHF, such as the direct eddy correlation method, bulk method, and inertial dissipation method. The direct eddy correlation method is the most reliable, because in this method, fluxes can be directly computed using high-frequency measurements of turbulent perturbations [*Fairall et al.*, 1996]. However, a ship motion correction for the wind velocity is needed in direct eddy correlation measurements over the ocean, because the platform (ship) is not stable. In addition, a sonic anemometer-thermometer, which is a very expensive sensor, is necessary for direct eddy correlation measurements. Due to these two issues, very few direct eddy correlation measurements have been performed [*Tsukamoto and Ishida*, 1995].

[4] On the other hand, the bulk method can estimate LHF by using a coefficient parameterized with meteorological variables that are more easily measured. In other words, we can easily estimate LHF by using the following bulk method

$$LHF = \rho_a L_v C_E |U_{air} - U_{sea}|(q_s - q_a), \tag{2}$$

where C_E is the bulk exchange coefficient for moisture, U_{air} is the wind speed at 10 m above the sea surface, U_{sea} is the surface current speed, and q_s and q_a are saturated and near-surface atmospheric specific humidities, respectively. In this study, U_{sea} is assumed to be zero since it is smaller than U_{air} except in equatorial regions. Although various researchers have proposed many bulk exchange coefficients, their values are different. Other differences among bulk methods include aspects such as whether the effect of the salinity of the seawater is considered in calculating the surface saturated humidity, whether the convective gustiness is considered at low wind speeds, and whether the warm layer and cool skin models are considered in estimating the bulk sea surface temperature to the skin sea surface temperature.

[5] Previously, the differences among some bulk methods have been extensively discussed by *Zeng et al.* [1998] and *Chang and Grossman* [1999] using direct eddy correlation fluxes. However, the results may not necessarily apply to the global ocean, because they only used research cruise data from tropical regions. On the other hand, *Brunke et al.*

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[2003] evaluated 11 bulk methods in not only the tropics but also the midlatitude regions; they performed hourly measurements of the direct eddy correlation fluxes and inertial dissipation methods by carrying out 12 field experiments using the research ships of the National Oceanic and Atmospheric Administration/Environmental Technology Laboratory (NOAA/ETL). Their results suggested that the COARE3.0 algorithm [*Fairall et al.*, 2003] is "one of the least problematic flux algorithms."

[6] Currently, we can use various satellite observation data for meteorological variables such as wind speed, air specific humidity, and sea surface temperature. Therefore, we can estimate the THF from satellite observation data using a bulk method. Recently, several global data sets of the ocean surface turbulent fluxes have been compiled that are based on satellite observation: IFREMER [*Bentamy et al.*, 2003], Goddard Satellite-Based Surface Turbulent Fluxes 2 (GSSTF2 [*Chou et al.*, 2003]), Japanese Ocean Flux Data Sets with Use of Remote Sensing Observation 2 (J-OFURO2 [*Kubota and Tomita*, 2007]), Hamburg Ocean-Atmosphere Parameters from Satellite Data 3 (HOAPS3 [*Andersson et al.*, 2007]), and Objectively Analyzed Air-Sea Fluxes (OAFlux [*Yu and Weller*, 2007]). COARE3.0 is used for all the data sets except GSSTF2.

[7] However, the following three questions arise when the LHF is estimated by applying COARE3.0 to the satellite data. First, COARE3.0 is an algorithm adjusted to not the bulk sea surface temperature but the skin sea surface temperature. Therefore, the warm layer and cool skin models are included in the COARE3.0 algorithm, and these models can estimate the temperatures from the bulk sea surface to the skin sea surface. These models require hourly (or shorter time interval) data of downward longwave and shortwave radiation. However, it is difficult to consider these effects for satellite-derived LHF, because accurate global downward longwave and shortwave radiation fluxes cannot be estimated at such a timescale using satellite data. *Donlon et al.* [2002] developed a model that can simulate the relationship between the bulk sea surface and skin sea surface temperatures using the surface wind speed. However, they reported that the model cannot accurately simulate the relationship during the day at wind speeds less than 6 m/s. Satellite-derived LHF has generally been estimated using the bulk sea surface temperature because accurate skin sea surface temperatures cannot be observed in the global ocean. Owing to the abovementioned reasons, we have to use the bulk sea surface temperature when estimating the global LHF from satellite data using COARE3.0. Therefore, we have a question in the accuracy of the LHF that is estimated with COARE3.0 using the bulk sea surface temperature instead of the skin sea surface temperature.

[8] The second issue is that COARE3.0 is an algorithm parameterized at an hourly timescale. However, satellite-derived LHF is generally estimated as a daily mean value from one or two observations, because sun-synchronous polar orbit satellites observe a particular location only once or twice a day. Therefore, we need to evaluate the accuracy of LHF estimated from the daily mean of meteorological variables using COARE3.0.

[9] The third issue is that in addition to the bulk method error, the observation and sampling errors of the meteorological variable are included in errors of the satellite LHF data. It is important to reveal LHF errors by including not only the error determined by the bulk method but also errors of the meteorological values. Therefore, we have to evaluate the LHF errors as a function of errors of the meteorological values.

[10] The purpose of this study is to determine the most accurate bulk method for estimating the satellite-derived LHF. We evaluate four bulk methods by using direct eddy correlation and inertial dissipation fluxes obtained during 15 cruises in the tropics and midlatitudes. As mentioned previously, similar comparisons have already been carried out [*Brunke et al.*, 2003]. However, this study is different in that we discuss three types of accuracies for the LHF when evaluating the bulk methods for analyzing satellite data: "the accuracy of the LHF estimated with COARE3.0 using the bulk sea surface temperature instead of the skin sea surface temperature," "accuracy of the LHF estimated from the daily mean of meteorological variables using COARE3.0," and "accuracy of the LHF including not only the error determined by the bulk method but also the meteorological value error." Also, we evaluate the accuracy of the satellite-derived LHF (J-OFURO2) by the direct eddy correlation fluxes.

[11] Section 2 describes the four bulk methods used in this study and presents the data obtained during the 15 ship cruises and the satellite data (J-OFURO2). Section 3 describes the analysis method used in this study. Section 4 shows the evaluation results for the four bulk methods using the data obtained during the 15 cruises. LHF errors as functions of meteorological value errors are presented in section 5. Section 6 gives comparison results of the satellite-derived LHF (J-OFURO2) with the direct eddy correlation fluxes. Finally, the summary and discussion are presented in section 7.

2. Bulk Methods and Data

2.1. Bulk Methods

[12] We evaluated four bulk methods: *Fairall et al.* [2003], *Chou et al.* [2003], *Kondo* [1975], and *Zeng et al.* [1998]. The difference in how the algorithms consider effect is listed in Table 1. We can see additional effects that are included in COARE3.0 compared to the other bulk methods. *Chou et al.* [2003] described an algorithm that is used by GSSTF2 products. Their algorithm was evaluated by direct eddy correlation measurements obtained during 10 ship cruises. This algorithm succeeded in estimating the flux with the same degree of accuracy as COARE3.0 [*Chou et al.*, 2003]. *Kondo*'s [1975] algorithm is used in J-OFURO1 LHF products [*Kubota et al.*, 2002]. This algorithm assumes a neutral atmosphere because it is difficult to observe accurate air temperature data using satellites. The salinity effect was not included by *Kondo* [1975] but is incorporated into J-OFURO1. Therefore, the salinity effect is applied to the models from both *Kondo* [1975] and J-OFURO1 in this study. *Zeng et al.*'s [1998] model was developed at the University of Arizona. This model is based on observation data from the COARE cruise.

2.2. Cruise Data

[13] In situ data are obtained from three sources. Ten data sets are provided from the experiments performed by the

Table 1. Difference in How the Algorithms Consider Effect

Algorithm	Convective Gustiness	Salinity Effect	Cool Skin, Warm Layer
Fairall et al. [2003]	Yes	Yes	Yes
Chou et al. [2003]	No	Yes	No
Kondo [1975]	No	Yes	No
Zeng et al. [1998]	Yes	Yes	No

National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL). Two data sets are obtained from the Centre d'Etude des Environnements Terrestre et Planetaires (CETP). Finally, three data sets are obtained from the Japan Agency for Marine and Earth Science Technology (JAMSTEC). Table 2 lists the periods and data numbers (hourly) for fifteen ship cruises: ASTEX, COARE, FASTEX, JASMINE, KWAJEX, MOORINGS, NAURU99, PACSF99, SCOPE, TIWE, CATCH, FETCH, MR02K03, MR02K06L01, and MR02K06L03. Figure 1 shows the locations of these fifteen cruises. The direct eddy correlation fluxes are available for all cruises, whereas inertial dissipation fluxes are available only for CATCH. Direct eddy correlation fluxes can be observed as continuous data for approximately 50 min, because the turbulent perturbation of the direct eddy correlation measurements have a high-frequency sampling of approximately 10 GHz. Therefore, these data points represent 50 min mean values. The 50 min samples of the direct eddy correlation measurements for LHF have a typical root-mean-square error include sampling uncertainty of 5 W/m^2 ± 20% [*Fairall et al.*, 1997]. The total number of direct eddy correlation flux data points used in this study is 3879; this number is approximately 1100 more than that used by *Brunke et al.* [2003]. In this study, we used cruise data to which various corrections had already been applied. Details of the correction for the JAMSTEC cruise have been reported by *Takahashi et al.* [2005] and those for the ETL and CETP cruises have been reported by *Brunke et al.* [2003]. Only the outline of the correction methods is shown in this study.

[14] Direct eddy correlation measurements are sensitive to the environmental conditions and flow distortion [e.g., *Yelland et al.*, 1998; *Edson et al.*, 1998; *Takahashi et al.*, 2005]. Details of the motion correction for the ETL, FETCH, and JAMSTEC cruises have been reported by *Edson et al.* [1998], *Brunke et al.* [2003], and *Takahashi et al.* [2000], respectively. Flow distortion due to the presence of the ship or platform affects both the mean and turbulent measurements, particularly for the wind. Corrections for mean wind speed and the height of measurements are based on wind tunnel measurements and wind flow patterns obtained through computational fluid dynamics (CFD) models. Height adjustments to observations are made according to *Yelland et al.*'s [1998] analysis for data taken aboard COARE, FASTEX, JASMINE, KWAJEX, MOORINGS, NAURU99, and TIWE. Details of the correction for FETCH have been reported by *Dupuis et al.* [2003]. Because no independent distortion estimates are available for ASTEX and CATCH, no height adjustments are made for these data sets.

2.3. Satellite Data

[15] In this study we evaluate accuracy of the satellite-derived wind speed, sea surface temperature, air specific humidity and the LHF using fifteen cruises data. The satellite data are included in the J-OFURO2 [*Kubota and Tomita*, 2007]. The wind speed data are derived from multiple satellite sensors: Defense Meteorological Satellite Program/Special Sensor Microwave Imager (DMSP/SSMI) F08, F10, F11, F13, F14, F15, Aqua/Advanced Microwave Scanning Radiometer-Earth observing system (Aqua/AMSR-E),

Table 2. Cruises From Which Data is Used in This Study

Experiments	Acronym	Institution	Ship or Platform	Time Period	Number of Data (Hourly)	SST Depth (m)
Atlantic Stratocumulus Transition Experiment	ASTEX	ETL	R/V *Malcolm Baldridge*	7–28 Jun 1992	112	0.05
Couplage avec 1' Atmosphere en Conditions Hivernales	CATCH	CETP	R/V *Le Suroît*	12 Jan to 1 Feb 1997	210	2.5
Coupled Ocean-Atmosphère Response Experiment	COARE	ETL	R/V *Moana Wave*	12 Nov 1992 to 16 Feb 1993	567	0.05
Fronts and Atlantic Storm Track Experiment	FASTEX	ETL	R/V *Knorr*	24 Dec 1996 to 26 Jan 1997	102	0.05
Flux, État de la Mer et Télédétection en Condition de Fetch Variable	FETCH	CETP	R/V *L' Atalante*	13 Mar to 15 Apr 1998	550	2.5
Joint Air-Sea Monsoon Experiment	JASMINE	ETL	R/V *Ronald H. Brown*	5–31 May 1999	139	0.05
Kwajalein Experiment	KWAJEX	ETL	R/V *Ronald H. Brown*	26 Jul to 12 Sep 1999	456	0.05
Buoy service in the North Pacific	MOORINGS	ELT	R/V *Ronald H. Brown*	14 Sep to 21 Oct 1999	112	0.05
MR02K03	MR02K03	JAMSTEC	R/V *MIRAI*	26 May to 21 Jun 2002	388	5
MR02K06L01	MR02K06L01	JAMSTEC	R/V *MIRAI*	13 Nov to 16 Dec 2002	430	5
MR02K06L03	MR02K06L03	JAMSTEC	R/V *MIRAI*	13–31 Jan 2003	290	5
The Nauru 1999	NAURU99	ETL	R/V *Ronald H. Brown*	15 Jun to 18 Jul 1999	257	0.05
Pan-American Climate Study in the Eastern Pacific during 1999	PACSF99	ETL	R/V *Ronald H. Brown*	22 Nov to 12 Dec 1999	11	0.05
San Clemente Ocean Probing Experiment	SCOPE	ETL	R/V *FLIP*	18–29 Sep 1993	242	0.05
Tropical Instability Wave Experiment	TIWE	ETL	R/V *Moana Wave*	25 Nov to 11 Dec 1991	13	0.05

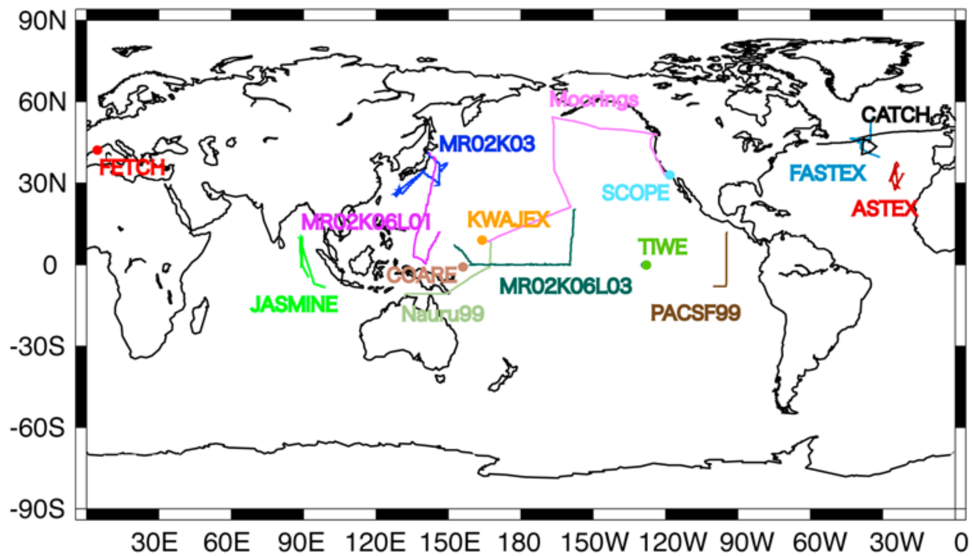

Figure 1. Ship trajectories for the 15 cruises.

Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (MI), European Remote-sensing Satellite (ERS) 1/2 and QuikSCAT. The algorithm proposed by *Schlüssel et al.* [1995] is used to compute the specific humidity data using the brightness temperature data observed by SSMI/F13, F14 and F15. The sea surface temperature is Japanese Meteorological Agency (JMA) merged satellite and in situ data global daily (MGD) sea surface temperature product. The sea surface temperature data are constructed by merging the in situ and satellite data of the AMSR-E and the Advanced Very High Resolution Radiometer (AVHRR) [*Kurihara et al.*, 2006]. COARE3.0 is used as a bulk method. Also, warm layer ad cool skin effects are not included in the J-OFURO2. J-OFURO2 product provides daily averages on a 1° grid.

3. Method

3.1. Comparison Methods

[16] We focus on the hourly and daily mean data. The hourly mean LHF are estimated by applying the four bulk methods to the hourly mean data of meteorological values measured during the 15 cruises. The daily mean LHF is estimated from the daily mean of meteorological values. We estimate the daily mean value only when more than nine meteorological values can be obtained per day. The number of hourly data used for estimating a daily mean value is 3089 in total number 3879.

3.2. Error Analysis Methods

[17] As mentioned in Section 1, not only the bulk method error but also the observation and sampling errors of the meteorological variable are included in the errors in the satellite LHF data. To clarify the errors in the LHF to include not only the bulk method but also the meteorological variable, we evaluate the LHF errors as an error function of the meteorological value. According to previous studies, the RMS errors of the daily mean for satellite data are 1–1.5 m/s for the wind speed [*Tomita et al.*, 2010], 0.3–0.5°C for the sea surface temperature [*Iwasaki et al.*, 2008], and 1–2 g/kg for the air specific humidity [*Kubota and Hihara*, 2008]. Generally we may assume that the distribution of RMS error for the meteorological values derived from a satellite data follows normal distribution. Therefore, we will carry out the error analysis related to the RMS errors in Section 5.

4. Evaluation of Bulk Method

[18] We evaluate the four bulk methods using the data obtained during the 15 cruises. For simplification, the LHF derived from the bulk and eddy correlation methods are denoted by LHF_B and LHF_D, respectively. Figure 2 shows the bias ($LHF_B - LHF_D$) between the hourly LHF estimated by each bulk method and that obtained by the eddy correlation method for three wind speed ranges. The subscript "nowc" for COARE3.0 means that warm layer and cool skin models are not applied. The bias for COARE3.0 is approximately 4 W/m^2 or less in all wind speed regions and is lower than that of the other bulk methods. The bias of COARE3.0$_{nowc}$ is higher than that of COARE3.0. However, the bias of COARE3.0$_{nowc}$ is lower than 10 W/m^2 in all wind speed regions. In contrast, the biases for the other bulk methods are higher than 10 W/m^2 for several wind speed ranges. The bias for Kondo's model is −12 W/m^2 at low wind speeds. At moderate wind speeds, the bias of Chou *et al.*'s model is 15 W/m^2. Finally, the bias for Zeng *et al.*'s model is −32 W/m^2 at high wind speeds. As mentioned in Section 1, Zeng *et al.*'s model is based on the COARE cruise. This cruise only provides data for tropical regions in low wind speed regions. Therefore, the bias of Zeng *et al.*'s model is large at high wind speeds. From the above results, we observed that the bias of COARE3.0 increases (4–5 W/m^2) if the warm layer and cool skin models are not applied. However, in terms of results, COARE3.0$_{nowc}$ can be considered to be more accurate than the other bulk methods since their biases are larger than 10 W/m^2 for several wind speed ranges. The RMS errors for the three wind speed ranges are shown in Figure 3. There are no large differences in the RMS error between different bulk methods. The RMS

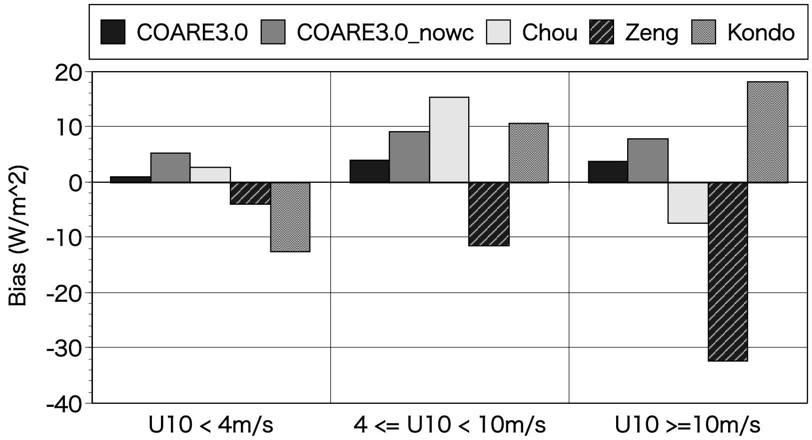

Figure 2. Bias ($LHF_B - LHF_D$) between hourly LHF estimated by each bulk method and that obtained by eddy correlation method for three wind speed ranges.

error also increases with the wind speed (approximately 53 W/m^2 at high wind speeds).

[19] The difference between COARE3.0 and COARE3.0$_{nowc}$ is whether the effect of the warm layer and cool skin models are included. The bias of hourly LHF (COARE3.0) for each of the 15 cruises is given in Figure 4. Here, the subscript "w" for COARE3.0 means that only the warm layer is considered, whereas the subscript "c" means that only cool skin models are applied. The biases of COARE3.0 and COARE3.0$_c$ have the same values except for MR02K03 and MR02K06L03. Therefore, using only the cool skin models influences the LHF of COARE3.0 excluding MR02K03 and MR02K06L03. One reason why the warm layer does not affect the LHF obtained during the cruises besides MR02K03 and MR02K06L03 is that sea surface temperatures are observed in the cool skin layer; this is because the depth at which the sea surface temperature is measured in ETL and CETP besides the JAMSTEC cruise is very shallow (in particular, ETL had a measuring depth of 0.05 m). On the other hands, one reason why the warm layer does affect the LHF obtained during MR02K03 and MR02K06L03 is that sea surface temperatures are observed under the warm layer only in these two cruises. The bias of COARE3.0 is lower than that of COARE3.0$_{nowc}$ in the cruises used for the parameterization of COARE3.0 (ASTEX, COARE, SCOPE, and TIWE). However, the bias of COARE3.0 is larger than that of COARE3.0$_{nowc}$ for the seven cruises not used in the parameterization of COARE3.0. From this result, the question arises whether COARE3.0 can accurately estimate the LHF compared with other bulk methods even for cruises not used in the parameterization of COARE3.0. Figure 5 shows the bias for cruises not used in the parameterization of COARE3.0. The bias is similar to the results shown in Figure 2. For example, these results show the underestimation by *Kondo*'s [1975] model in the low wind speed region, overestimation by *Chou et al.*'s [2003] model in the moderate wind speed region, and underestimation by *Zeng et al.*'s [1998] model in the high wind speed region. The biases of COARE3.0 and COARE3.0$_{nowc}$ are lower than for the other bulk methods. Therefore, we concluded that COARE3.0 and COARE3.0$_{nowc}$ can also provide more accurate LHF for cruises not used in the parameterization of COARE3.0 compared with other bulk methods.

[20] As mentioned in Section 1, the satellite-derived THF is generally used as a daily mean value. Thus, the accuracy of the bulk method for the daily but not hourly mean value is

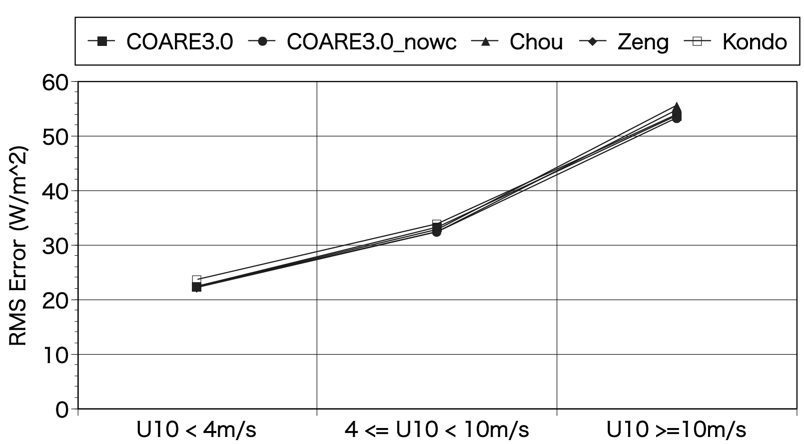

Figure 3. RMS error between hourly LHF estimated by each bulk method and that obtained by eddy correlation method for three wind speed ranges.

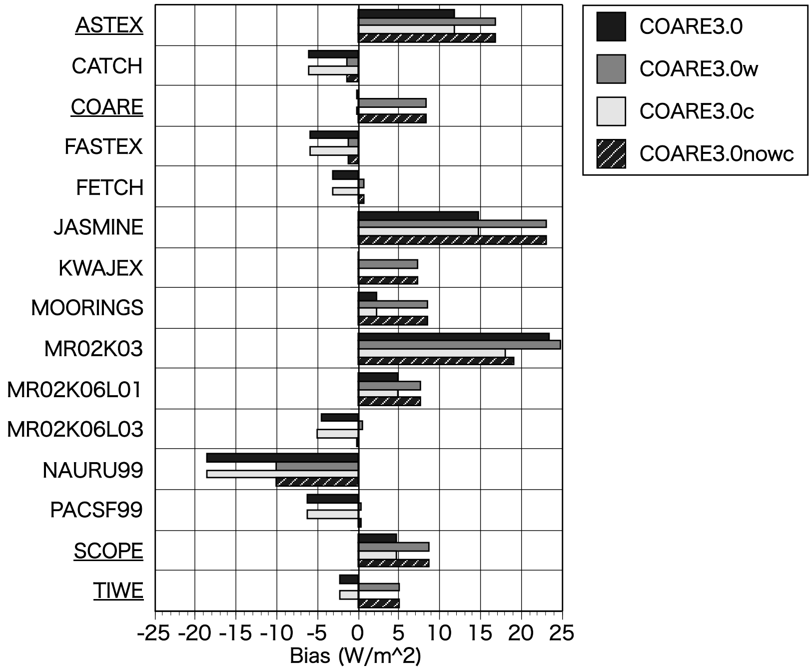

Figure 4. Bias ($LHF_B - LHF_D$) of hourly LHF (COARE3.0) for each of the 15 cruises. Underlined cruises are those used in the parameterization of COARE3.0.

important for the satellite-derived THF. Here, we evaluate the accuracy of the bulk methods for the daily mean value. We estimate a daily mean value only when more than nine meteorological values can be obtained per day. Figure 6 shows the bias between the daily LHF derived from an eddy correlation method and that for each bulk method for three wind speed ranges. The bias of COARE3.0$_{nowc}$ is smaller than that of the other bulk methods. This result shows that COARE3.0 can accurately estimate LHF for not only hourly but also daily mean values. This means that COARE3.0 is the best algorithm even when LHF is derived from a daily mean of the satellite data. The biases of all bulk methods except COARE3.0$_{nowc}$ are larger than 10 Wm^2 at high wind speed regions (in particular, the bias of *Zeng et al.*'s [1998] model is −40 W/m^2). Figure 7 shows the RMS error of the daily LHF_B and LHF_D. The RMS error increases with the wind speed (approximately 42–50 W/m^2 at high wind speed). In addition, there are no large differences in the RMS errors among the bulk methods. The RMS error for all wind speed regions is 18–22 W/m^2. The values are 12–18 W/m^2 lower than that of LHF derived from hourly meteorological value, as shown in Figure 3.

5. Error Analysis

[21] We evaluated the LHF errors as an error function of meteorological values. Here, we used several meteorological values including the RMS errors for the daily mean of cruise data. As mentioned in Section 3, we used a normal random number that mean value is 0 for RMS error. We constructed LHF data by using several meteorological values including

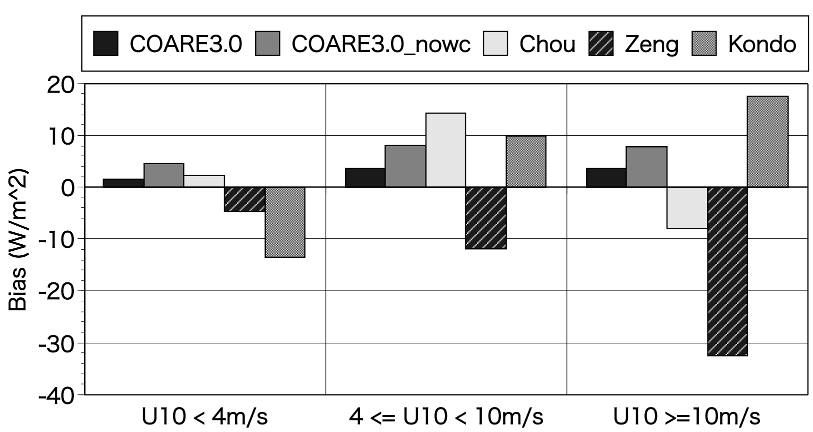

Figure 5. Bias ($LHF_B - LHF_D$) for cruises not used in the parameterization of COARE3.0.

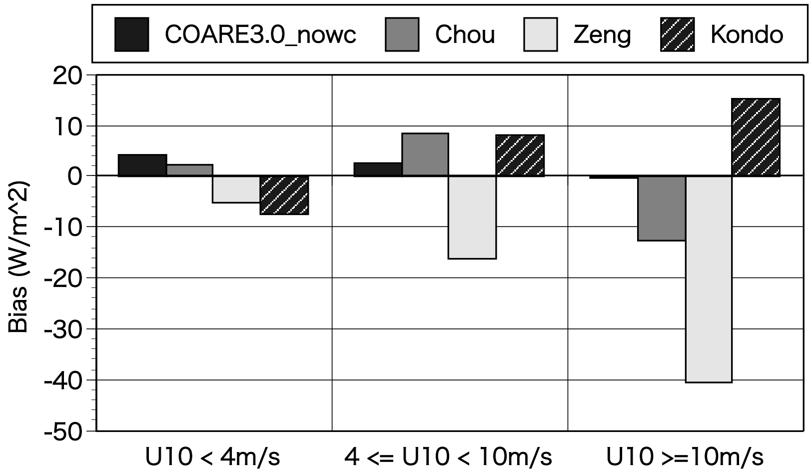

Figure 6. Bias ($LHF_B - LHF_D$) between daily LHF derived from eddy correlation method and each bulk method for three wind speed ranges.

the RMS errors. For the simplification, the RMS errors of the LHF as functions of wind speed, sea surface temperature, and air specific humidity are denoted by ΔLHF (ΔC_e,ΔU_{10}), ΔLHF(ΔC_e,ΔT_s), and ΔLHF(ΔC_e,ΔQ_a). Moreover, these RMS errors include the bulk method error. Figure 8 shows the RMS error of the LHF as a function of the RMS error for several meteorological values. The vertical axis indicates the RMS error between the daily LHF derived from COARE3.0_{nowc} and LHF$_D$. Corresponding to the RMS error of each meteorological value obtained in the previous study, we find that ΔLHF(ΔC_e,ΔU_{10}) is 24–29 W/m^2, ΔLHF(ΔC_e,ΔT_s) is 20–23 W/m^2, and ΔLHF(ΔC_e,ΔQ_a) is 30–50 W/m^2, as shown in Figure 8. This result means that the RMS error of the air specific humidity largely contributes to that of the LHF. Evaluations of the global LHF data by means of observations from surface-moored buoys have been carried out in several oceans [*Bourras*, 2006; *Tomita and Kubota*, 2006]. These studies concluded that the accuracy of satellite-derived LHF primarily depends on the accuracy of satellite-derived air specific humidity. Therefore, the results of this study correspond to their results.

[22] When the LHF is derived from the satellite data, the RMS error is affected by not one but all meteorological values. The RMS errors of daily COARE3.0 LHF as a function of wind speed and air specific humidity are shown in Figure 9. The analysis method is the same as the above mentioned method. The RMS error of each meteorological value is given as a normal random number and is shown in Figure 8. Here, the RMS error of the sea surface temperature is assumed to be 0.5°C. If the RMS error of the sea surface temperature is assumed to be 0.3°C, the RMS error of Figure 9 reduces to only 1–2 W/m^2 (not shown here). The contour shows that the RMS errors of LHF$_D$ and LHF are derived from COARE3.0_{nowc} (5 W/m^2 interval). We can see that the RMS error strongly depends on not the wind speed but air specific humidity. This result corresponds to the results shown in Figure 8. In addition, if we assume the RMS error of the satellite derived meteorological values

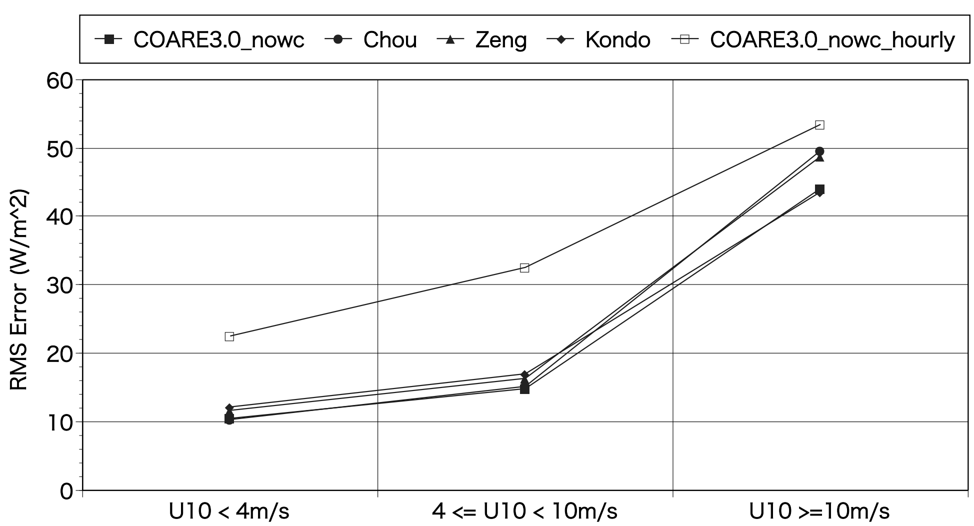

Figure 7. RMS error between daily LHF estimated by each bulk method and that obtained by eddy correlation method for three wind speed ranges.

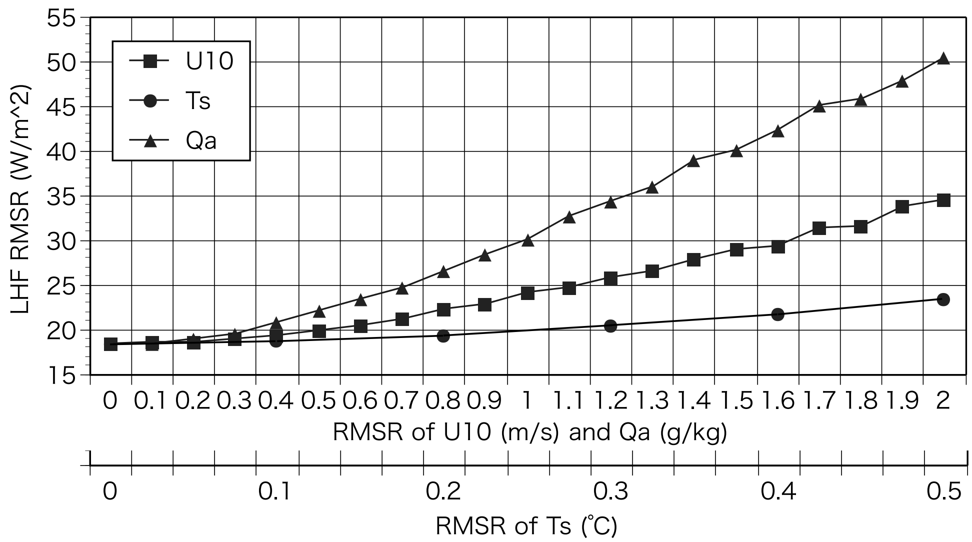

Figure 8. RMS error of LHF as an error function for several meteorological values (i.e., wind speed, air specific humidity, and sea surface temperature).

at present (wind speed: 1–1.5 m/s, air specific humidity: 1–2 g/kg), the accuracy of the LHF obtained from the satellite data is approximately 35–55 W/m^2.

6. Comparison Between Satellite and Cruise Data

[23] In the previous section we carried out an error analysis based on the RMS errors of each meteorological variable given. In order to identify the analysis results are the case for the real data or not, we compare the meteorological variables and LHF, derived from satellite (J-OFURO2) and in situ observation. To collocate the satellite data with cruise locations, we construct matchup data by interpolating data on four grid points into a cruise location. In addition, we estimate the daily mean value only when cruise data exist data ten or more a day. As a result, the data number is 146. Statistics between J-OFURO2 and cruise data are listed in Table 3. From Table 3, the air specific humidity was overestimated (1.12 g/kg). This overestimation leads to underestimation of LHF. The RMS errors are 1.29 m/s for the wind speed, 0.51°C for the sea surface temperature and 1.21 g/kg for the air specific humidity, respectively. These RMS error values are consistent with previous results as described in Section 5. We can obtain about 41 W/m^2 if we estimate the RMS error of the LHF using Figure 9 from the RMS error of meteorological values in Table 3. The result of Figure 9 is practicable because this RMS error of the LHF is roughly equal to the RMS error (37 W/m^2) of the LHF in Table 3. Although the correlation coefficients of each meteorological value are high, 0.88–1, that of the LHF is low, 0.69. This result means that the error of bulk method is considerably contributed to error of the LHF.

[24] Moreover, to investigate the dependency of the error of the LHF on those of the bulk method and the meteorological values of J-OFURO2, we analyzed the error of the LHF by using the same method as *Tomita and Kubota* [2006] and *Kubota et al.* [2008]. We used the daily mean meteorological value from cruise, systematically substituting one meteorological value into that from J-OFURO2 (these data sets are hereafter referred to as substitute data sets). The substitute and statistics between LHF_D and each substituted data set for the LHF are listed in Table 4. The values in parentheses are the results compared with the Substitute 1. The Substitute 1 gives the error of the LHF due to the bulk method error. The Substitute 2–4 gives the error of the LHF due to the parameter of J-OFURO2, including the bulk method error. The error of the LHF only due to the meteorological value of J-OFURO2 is shown in parentheses of Substitute 2–4. From the Table 4 the large bias is found in the Substitute 4 (about −21 W/m^2). In other words the negative bias of LHF is due to the overestimation of the air specific humidity. However, the bias of the LHF is small

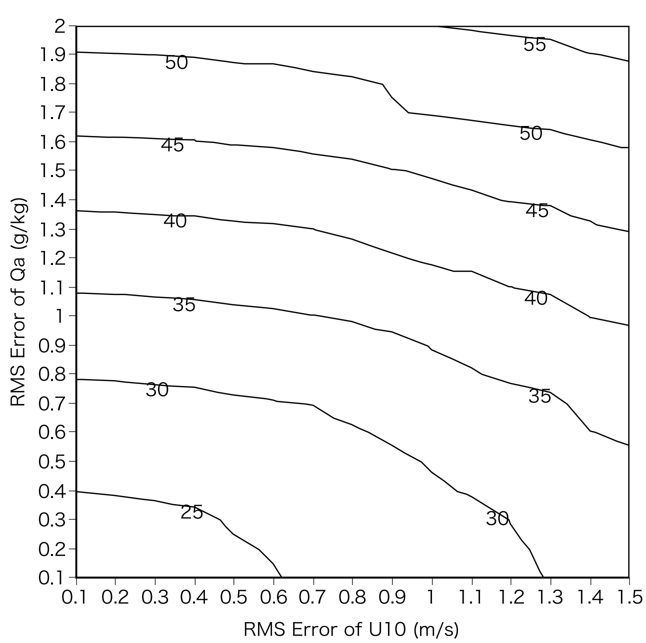

Figure 9. RMS errors of daily COARE3.0 LHF as a function of wind speed and air specific humidity.

Table 3. Statistics Between J-OFURO2 and Cruise

	U_{10} (m/s)	T_s (°C)	Q_a (g/kg)	LHF (W/m^2)
Bias[a]	0.62	0.03	1.12	−10.8
RMS Error	1.29	0.51	1.21	36.56
Correlation	0.88	1	0.97	0.69

[a]Bias is J-OFURO2 minus cruise.

(−10 W/m^2) shown in Table 3 because the bulk method (2.5 W/m^2), U_{10} (9.0 W/m^2) and T_s (0.8 W/m^2) give positive biases. The large RMS error (33 W/m^2) is observed in the Substitute 4 including bulk method error. Next, the RMS errors are 26 W/m^2 for the Substitute 2 and the 20 W/m^2 for the Substitute 3, respectively. When estimating the RMS error of the LHF by using Figure 8 from the RMS error of each meteorological value (the wind speed: 1.3 m/s, the sea surface temperature: 0.5°C and the air specific humidity: 1.2 g/kg) in Table 3, ΔLHF(ΔC_e,ΔQ_a) is 34 W/m^2, ΔLHF(ΔC_e,ΔU_{10}) is 26 W/m^2 and ΔLHF(ΔC_e,ΔT_s) is 23 W/m^2. These results are extremely consistent with the RMS error in Table 4. Therefore, the results of Figure 8 are practicable. We can see for 25.6 W/m^2 for Substitute 4, 19.8 W/m^2 for Substitute 2, 17.3 W/m^2 for Substitute 1 and 14 W/m^2 for Substitute 3 in the parentheses. In other words the factor influencing the RMS error of the LHF is the air specific humidity, the wind speed, the bulk method and the sea surface temperature in order.

7. Summary and Discussion

[25] The purpose of this study is to determine the most accurate bulk method for estimating the satellite-derived LHF. In this study, we evaluated four bulk methods (COARE3.0, Chou, Kondo, and Zeng) by using the direct eddy correlation and inertial dissipation fluxes obtained during the 15 cruises in the tropics and midlatitudes. In the results, we noticed that the bias of COARE3.0 increases (4–5 W/m^2) if warm layer and cool skin models are not applied to COARE3.0. However, in terms of results, COARE3.0$_{nowc}$ can be considered to be more accurate than the other bulk methods because their biases are larger than 10 W/m^2 in several wind speed ranges. In other words, COARE3.0 is the best algorithm for satellite-derived LHF even if warm layer and cool skin models are not applied.

[26] The bias of COARE3.0 is larger than that of COARE3.0$_{nowc}$ for the seven cruises that are not used for the parameterization of COARE3.0. Therefore, for the warm layer and cool skin models of COARE3.0, it is possible that accurate skin sea surface temperatures cannot be estimated for other regions. *Castro et al.* [2003] evaluated the accuracy of four models that estimate temperatures from the bulk sea surface to the skin sea surface. They indicated that the accuracy of the skin sea surface temperature from *Fairall et al.*'s [1996] model is low, because the correlation coefficient between the in situ value and the derived skin sea surface temperature is 0.36. Unfortunately, we cannot evaluate the accuracy of this model since the skin sea surface temperature is not included in the used data. However, it is necessary to improve the warm layer and cool skin models included in COARE3.0.

[27] In addition, to clarify the error of the satellite-derived LHF including the errors in the meteorological values, we evaluated the LHF errors as an error function of the meteorological value. If we assume the reported RMS errors of the satellite-derived meteorological values to be valid, the accuracy of the LHF is approximately 35–55 W/m^2. The RMS error of air specific humidity contributes to most of the RMS error of the LHF. The bulk method error contributes to 30–50% of the RMS error of the LHF. Therefore, the bulk method error cannot be neglected, even though the air specific humidity is the most important factor for accurate improvement of the satellite-derived LHF.

[28] Moreover, in order to identify the analysis results are applicable for the real data or not, we compared meteorological values and the LHF derived from satellite (J-OFURO2) with those by in situ observation. When calculating the RMS error of the LHF by applying results of error analysis (Figure 9) from the RMS error of all meteorological values of satellite data (Table 3), the RMS error of the LHF is about 41 W/m^2. The result of Figure 9 is practicable because the RMS error of 41 W/m^2 is roughly equal to the RMS error (about 37 W/m^2) of the LHF derived from satellite data (Table 3). *Chou et al.* [2003] also compared meteorological value and the LHF derived from satellite data (GSSTF2) with those from cruise data. Their results revealed that the RMS error of the LHF (daily) is about 36 W/m^2. This RMS error is corresponded with present study's results (about 37 W/m^2). Moreover, to evaluate the dependency of the error of the LHF on the errors of bulk method and meteorological value of J-OFURO2, we analyzed the error of the LHF. As the results, the large RMS error (33 W/m^2) is observed for the LHF due to air specific humidity error including the bulk method error. If we estimate the RMS error of the LHF using error analysis results (Figure 8) from the RMS error of each meteorological value (Table 3), these RMS errors consistent with that given in Table 4.

[29] Finally, the air specific humidity is the key parameter for the accuracy of the satellite-derived LHF. Recently, *Kubota and Hihara* [2008] developed a new algorithm to estimate the air specific humidity from the brightness temperature observed by AMSR-E. The results revealed that the air specific humidity derived from their algorithms can reduce the RMS error by 0.6–0.9 g/kg compared to that derived from an existing algorithm. If the accuracy

Table 4. Substituted Data Sets of J-OFURO2 and the Statistics Between Cruise and Each Substituted Data Set for LHF[a]

Data Set	U_{10}	T_s	Q_a	Bias	RMS Error	Correlation
Substitute 1	Cruise	Cruise	Cruise	2.46	17.3	0.93
Substitute 2	J-OFURO2	Cruise	Cruise	11.44 (8.98)	26.11 (19.8)	0.85 (0.91)
Substitute 3	Cruise	J-OFURO2	Cruise	3.21 (0.75)	20.22 (14)	0.9 (0.95)
Substitute 4	Cruise	Cruise	J-OFURO2	−18.61 (−21.07)	33.19 (25.6)	0.73 (0.81)

[a]Units are in Wm^{-2}, except for the correlation. The values in parentheses are the results compared with Substitute 1.

improvement is applied to the RMS error in Figure 9, the RMS error of the LHF decreases to 12–18 W/m^2. The results shown in Figure 9 are quite useful for showing the dependency of the error of the LHF on the errors of meteorological values.

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